EFFECTS OF BASE TYPE ON THE PERFORMANCE OF JOINTED PLAIN CONCRETE PAVEMENTS

Subtask to Caltrans Task Order 11

Report Prepared by

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1. INTRODUCTION

The base course layer directly beneath a jointed plain concrete pavement (JPCP) is known to have a big impact on the overall performance of the pavement. The purpose of this report is to document the effect of the base course on performance of JPCP through results from extensive field tests conducted throughout the US and from results of mechanistic based performance prediction models.

Although current empirical design procedures such as AASHTO's indicate that the base layer provides only minimal structural capacity to the pavement, this may be misleading. Experience has shown that a base course can provide several advantages, including:

- A construction platform, thereby increasing initial smoothness of the JPCP;
- Increase the strength and uniformity of foundation support, especially over the long term, by limiting erosion and loss of support along with helping to bridge soft or weak areas of subgrade that may result in settlement and slab cracking;
- Provide good subdrainage to the pavement to minimize erosion of underlying layers.

The overall performance of JPCP depends on how well distresses in the pavement are controlled. In comparing the performance of JPCP sections with different base types, it is to be recognized that the effects of other design features and site conditions (such as joint spacing, slab thickness, subgrade support, presence of load transfer devices, climatic conditions, and magnitude of traffic loads) cannot be ignored. All these factors are integrated into the overall performance of JPCP sections, and it is usually difficult to isolate the effect of only the base type unless all other factors are common to pavements with different base types. For example, a given base may perform well with one level of traffic, but if the traffic load increases significantly, the same base may not perform well due to higher erosion.

In addition, for any given base type there is a wide range of quality that has and can be achieved. For CTB, the amount of cement and compaction are critical to its strength and erosion resistance. For ATB and PATB, their ability to resist stripping (dependent on several factors) is critical to their erosion resistance. For an unbound aggregate base, the gradation is critical to its ability to resist erosion.

Other Effects

In studying the effects of base layers on pavement performance, it is also prudent to simultaneously consider the confounding effects of other design and site features, such as joint spacing, slab thickness, presence of dowels, drainage characteristics, traffic, etc. In many cases, however, the benefits provided by one aspect can be offset by another, and therefore the performance can be solely attributed to the base type. Brief discussions of the factors that isolating the effect of base type on JPCP performance are presented in this section.

Drainage: The performance of a base type depends on the drainage characteristics of the layer and the drainage features provided in the pavement design. In general, permeable bases reduce faulting by 50 percent or more compared to bases without permeable bases (Khazanovich, 1998). The effect is more pronounced in the case of treated bases; in other words, permeable cement treated base (PCTB) and permeable asphalt treated base (PATB) are far superior to dense graded cement treated base (CTB) and asphalt treated base (ATB), respectively. Providing edge drains in the pavement allows free moisture to drain from the underlying support layers and controls faulting.

Climate: The climatic conditions, especially with regard to the amount of moisture in the base/subbase layers, have a profound effect on JPCP performance. Joint faulting increases with the presence of free moisture in the base, so pavements in climates with high precipitation and where the base remains moist for extended periods (i.e., without freeze periods) are prone to larger faulting. Again, the drainage provided in the design can confound the effects of climate on pavement faulting. Cold climates result in increased joint faulting due to increased joint openings. Climates with high solar radiation cause higher temperature gradients in the slab, increasing transverse cracking. Positive temperature and moisture gradients cause higher tensile stresses at the bottom of the slab, and negative gradients cause tensile stresses at the top of the slab, adding to load-related stresses and increasing the potential for slab cracking.

Dowels: The presence of dowels enables far better load transfer and reduces differential edge deflections and resulting joint faulting. The use of adequate dowels is, by far, the most effective factor in controlling joint faulting. The impact of the base course is significantly diminished when dowel bars are used and is more significant when they are not used. Treated bases provide increased joint load transfer and thus reduce joint faulting.

Widened lanes: The use of a widened lane reduces edge stresses and can significantly decrease transverse cracking. A widened lane reduces the magnitudes of the corner deflections, because the wheel loads pass at a significant distance from the slab edge, thus resulting in lower joint faulting. This is true for both non-doweled and doweled joints.

Traffic and age: Higher traffic volumes and heavier wheel loads increase both transverse cracking and faulting in JPCP. Transverse cracking is primarily caused by fatigue damage, i.e. exceeding the fatigue-resistant capacity of the JPCP that results from overloads and heavy traffic on the section. Similarly, faulting increases with more and more pumping of fines with the passing of traffic loads. The base type and design must be matched with the design traffic and desired life of the JPCP section.

Joint spacing and thickness: The slab geometry and thickness influence the stresses and deflections in the slab, which in turn affect transverse cracking and joint faulting in JPC pavements. The base course interacts with joint opening and closing through slab-to-base friction. The greater the friction, the lower the joint movements and, consequently, the lower the faulting that occurs.

Concrete properties: Concrete material and strength properties have a big impact on the stresses, strains, and deflections in the slab. Therefore, these properties significantly influence the potential the development of distresses in JPC pavements.

Several field studies have been undertaken to examine the effects of the various structural design features, climate, subgrade, and traffic on JPCP performance. Two such comprehensive studies that have looked into the effects of base type in the performance of JPCP are the Long Term Pavement Performance (LTPP) program and the FHWA Rigid Pavements Performance and Rehabilitation (RPPR) study (Owusu-Antwi, E.B. et al., 1998, Smith et al., 1998, Khazanovich, et al., 1998, Titus-Glover, L., 1999, Jiang et al., 2001).

In the LTPP study, the test sites designed for the strategic study of structural factors for new rigid pavements (Special Pavement Studies experiment #2, SPS-2), and the test sites containing in-service JPCP sections with different base and subbase types and structural features (General Pavement Studies experiment #3, GPS-3) have been used to evaluate the effects of base type on the performance of JPCP. The RPPR study used in-service highway field performance data from 15 different states (14 in the USA and 1 in Canada), and one of the objectives of this study was to evaluate the performance of different rigid pavement design features on in-place pavement sections under different environmental and traffic loading conditions. The design features that were considered in this evaluation included slab thickness, joint spacing, joint orientation, joint load transfer, joint sealant, base type, drainage, shoulder type, widened lanes, reinforcement, and pavement type. Figure 1 shows the distribution of RPPR and LTPP sections in the USA.

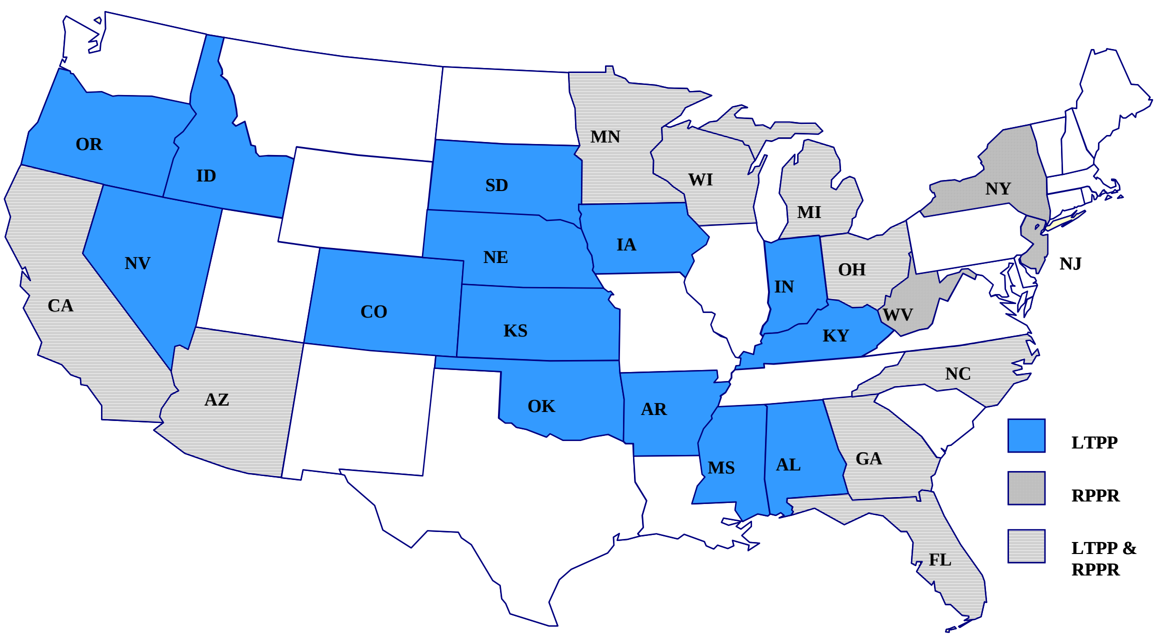

Figure 1. States with LTPP and RPPR field sections

Organization of Report

Section 1 of this report gives a brief introduction to the effect of base type on pavement performance and provides a brief background to two studies, LTPP and RPPR, each of which evaluated these effects. Section 2 of the report gives a brief summary of findings from these two studies. Next, Section 3 of the report presents a statistical analysis of the entire LTPP database from the relevant SPS-2 and GPS-3 sites as well as the RPPR database, performed as part of the Task 11 study for Caltrans. The analysis performed as part of this task is then used to support the recommendations for base types to be used for JPCP sections. Section 4 discusses how base type effects are incorporated in JPCP design.

2. SUMMARY FINDINGS FROM RPPR AND LTPP FIELD DATA

This section of the report summarizes the findings from the LTPP and RPPR studies. A majority of the findings presented are from previous studies cited in the references. However, in cases where specific information was unavailable from past literature, required data were extracted and analyzed to present the results in the context of the discussion presented. Since the RPPR study was of particular interest, a subsection of the report, FHWA-RD-95-110, on the RPPR study is included in Appendix A, providing a discussion of the effect of base type on the rigid pavement performance in each State and summarizing the findings. The RPPR database contains performance data for different slab lengths and levels of traffic. Appendix B contains a summary of average faulting, cracking, and International Roughness Index (IRI) in the RPPR sections for each base type and slab length. The associated level of average traffic is also tabulated for each category.

As noted earlier, the performance of a given base layer is also dependent on other design features, the local precipitation, and traffic loads. Base layer requirements vary widely, depending on all these factors, and can considerably alter the economics of the design. Pavements with residential traffic might not even require a base layer, while special base designs may be required for pavements that experience heavy traffic loads.

The stiffness or modulus of base courses as exists in the field are of interest because the layer modulus contributes to its structural contribution. Backcalculation of FWD data was performed on all rigid pavement sections in the LTPP database and the resulting means and ranges of base modulus values are shown in Table 1. The mean results are fairly typical of laboratory-measured moduli for these materials. The range for any given material, however, is very broad, indicating a wide range of material quality.

For the RPPR study, the base moduli were backcalculated from Falling Weight Deflectometer (FWD) data. The backcalculation was based on a two-layer slab on grade analysis and the modulus of the base was determined using suitable values for the ratio of the concrete modulus to the base modulus. For stabilized bases in the RPPR sections, the database contains the percentage of binding material used in the stabilization process, as shown in Table 2. The values shown in Table 2 are good indicators of the strength and durability of the base materials used in the RPPR field sections.

Table 1. Backcalculated base modulus of LTPP rigid pavements (Titus-Glover et al., 1998).

Base type	Backcalculated Base Modulus, MPa (ksi)		
	Minimum	Average	Maximum
LCB	1896 (275)	14472 (2099)	21001 (3046)
CTB	3406 (494)	6205 (900)	15134 (2195)
ATB	1648 (239)	2227 (323)	3565 (517)
PATB	1951(283)	2089 (303)	2358 (342)
AGG	179 (26)	228 (33)	283 (41)

Table 2. Percentage stabilization for bases in the RPPR study (Smith et al.).

Base type	Percentage Stabilization		
	Minimum	Average	Maximum
Soil cement	8 %	8.6 %	11.5 %
PCTB	5.2 %	6.9 %	8.3 %
PATB	1.5 %	2.2 %	3.0 %
LCB	6.9 %	7.5 %	10.0 %
CTB	4.0 %	4.8 %	6.0 %
ATB	2.5 %	3.8 %	8.0 %

From the RPPR and LTPP data analysis, in general, a higher level of distresses with increasing traffic was observed in pavements without a base layer (i.e., a slab on grade condition) than in pavements with a well-designed base layer. This was primarily a result of excessive pumping of fines from the subgrade, leading to joint faulting.

Granular bases considerably reduce pumping of subgrades. However, the extent of pumping (and the resulting faulting) is influenced by the differential deflections at the joint and the number of load repetitions. Therefore, those pavements with higher traffic and without adequate load transfer at joints experience much more faulting than those with doweled joints. The good performance noted in the JPCP sections with granular bases at the AASHO Road Test can be attributed to adequately sized dowel bars (dowel bar diameter was 1/8th of the slab thickness for each section) used in the transverse joints. These pavements did not have significant joint faulting during the 1.114 million axle load repetitions, even though the base layer was wet and experienced pumping. Furthermore, maintaining the base layer in a dryer condition reduces pumping and joint faulting. In general, granular bases have performed well in dry climates, such as in parts of Arizona.

Treated bases, on the other hand, were effective in reducing pumping and controlled joint faulting significantly. Several studies, including NCHRP 1-19 and the RPPR studies, have shown that undoweled pavements had as much as 33 percent lower joint faulting with treated bases than with untreated bases. Although the same trend was also observed in doweled pavements, the effect of using a treated base is not as significant because joint faulting is, in the first place, limited with the use of doweled joints. However, the use of a stiff treated base increased transverse cracking on JPCP sections.

The performance of "young" pavements, i.e., pavements 2-7½ yrs of age, was investigated in an LTPP study on an initial evaluation of SPS-2 sections (Jiang et al., 2001). Only 28 percent of the 155 sections showed any noticeable distresses within approx. 7½ years. These early performance trends need not necessarily reflect the long-term performance, because premature failures and distresses can also be as a result of poor construction quality or the use of "marginal" materials.

Effect of Base Type on Faulting

The quality and strength of the base type and the other design features significantly affect the faulting characteristics of jointed concrete pavements. Faulting is a direct result of increased differential deflections across joints and pumping of fines from the base layer. This makes the use of dowels across joints effective in controlling faulting by reduced differential deflections. Further, the use of permeable bases to reduce moisture retention in the base, and the use of bases with less fines to reduce pumping, are also effective in controlling faulting. As with all other distresses, past performance data can be used to identify those bases and their characteristics that make them suitable for good faulting performance.

In general, field data from RPPR and LTPP sections have shown that treated bases control faulting better than untreated granular bases, for both doweled and undoweled sections. Table 3 gives a summary of average joint faulting in doweled and undoweled pavements with treated and untreated bases in the LTPP and RPPR test sites. The data in Table 3 also illustrate the benefits of using dowels to control differential deflections that lead to faulting. The average faulting in the doweled sections were 2-4 times lower than in undoweled sections for both treated and untreated bases.

Table 3. Mean joint faulting from LTPP and RPPR data, mm (inches).

Test	Base Type	Undoweled	Doweled
LTPP	Non-Treated Base (aggregate)	2.78 (0.109) N = 65	0.72 (0.028) N=131
	Treated Base (asph., cement)	1.58 (0.062) N = 87	0.47 (0.018) N=109
RPPR	Non-Treated Base (aggregate)	2.14 (0.084) N =39	1.05 (0.041) N=37
	Treated Base (asph., cement)	2.10 (0.083) N = 100	0.87 (0.034) N=26

The advantage of using permeable bases and treated bases to keep moisture out of the pavement system, and therefore control faulting, was also evident in the RPPR field data. Sections on permeable bases or lean concrete bases (LCB) showed the least tendency to undergo faulting for both doweled and undoweled pavements (see Appendix A). Furthermore, for a traffic level of 10 million equivalent single axle loads (ESALs), RPPR sections had an average joint faulting of 3.1 mm (0.122 in), 2.4 mm (0.094 in), and 1.7 mm (0.067 in) for granular bases, treated bases and permeable bases, respectively. The advantage of using treated bases, permeable bases, and doweled joints is evident from these data. Based on data from these studies, a faulting model was developed for the design of JPC pavements. The model presented in Figure 2 accounts for the effects of the unbound base gradation, permeability of the base, and the size of the dowel in determining faulting.

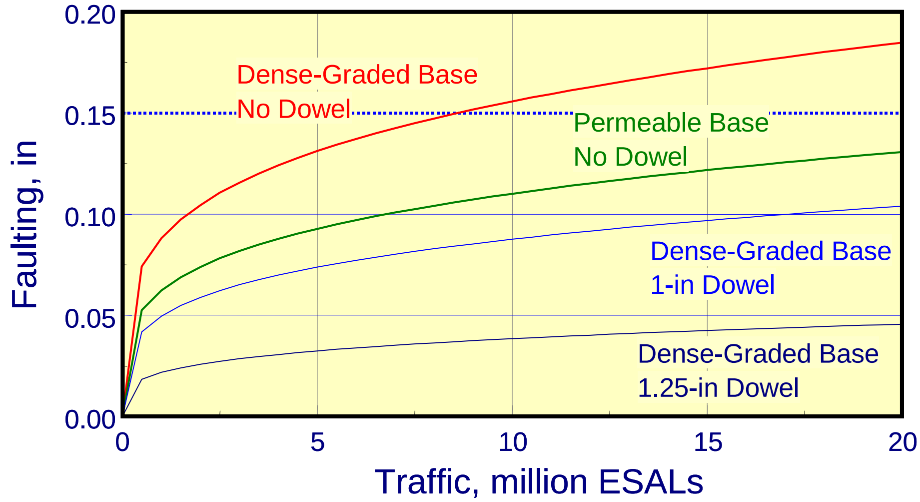

Figure 2. Faulting model from developed based on RPPR and LTPP database.

Amount of stabilization: It was also noted that the amount of stabilizing material used in the stabilized base had an impact on the observed faulting. Materials with a larger amount of stabilizing agent are less prone to erosion and, therefore, reduce the potential for faulting. For example, bases with more than 8 percent cement stabilization showed distinctly less faulting. Similarly, asphalt treated bases with about 6 percent asphalt stabilization showed less faulting than those with less stabilizing agent.

Early Age Faulting: Early age joint faulting in SPS-2 sections is shown in Figure 3 (Jiang et al., 2001). Note that these values are the maximum mean faulting values recorded over the 2 to 7½ year life of the JPCP section. It is also interesting to note that only 7 of the 155 sections had faulting levels of over 1mm (0.04 in). Six of these sections were constructed on an aggregate base and one on a lean concrete base.

As discussed in the previous sections, in interpreting data from Figure 3, it is to be noted that there might be reasons beyond the category type used in the bar charts that could have contributed to the faulting characteristics. For example, out of the seven sections that had greater than 1 mm (0.04 in) faulting, two were from Nevada and three from Michigan. The sections in Michigan were heavily trafficked, while those in Nevada failed prematurely because of poor concrete quality (Stubstad, 2002). It is also likely that some categories have more data than the others making it a more accurate mean.

As shown in Figure 3, early age faulting was most prevalent on aggregate bases and least prevalent on permeable treated bases with drainage and LCB. As expected, widened lanes reduced joint faulting considerably. Detailed analyses of early age faulting from LTPP and RPPR field data are presented in Section 3 of this report. It was also noted that sections in the wet-no freeze climatic zone showed the least early age joint faulting and those in the dry-freeze zone showed the highest. This trend in reduced joint faulting is difficult to explain, but it should be noted that sections in Nevada with very high faulting values in general belong to the dry-freeze climatic zone, thus increasing the average faulting in the dry-freeze climates.

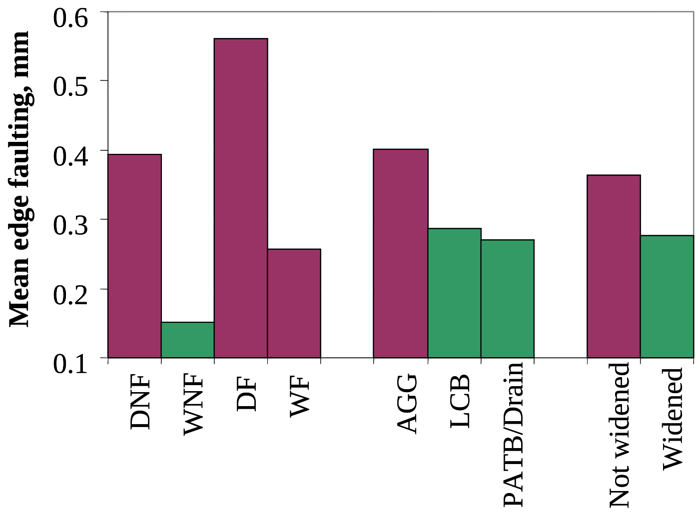

Figure 3. Early age joint faulting of doweled JPCP in LTPP SPS-2 sections (Jiang et al., 2001).

Effect of Base Type on Transverse Cracking

Slab cracking is also affected by the quality and strength of the base type. The stiffness of the base material is a very critical factor in the development of transverse cracking. Although stabilized and stiffer bases improve the overall bending stiffness of the composite system, very stiff bases increase curling stresses resulting from the separation of the base from the slab (Khazanovich et al., 1998). Field data has also statistically supported the fact that good quality aggregate bases and asphalt treated bases both show good performance and result in decreased cracking (Khazanovich et al., 1998).

In general, the RPPR data showed that sections on a stiff base showed higher levels of transverse cracking in JPCP pavements (Smith et al., 1998). However treated bases and bases with sufficient drainage showed better performance than untreated bases. Cracking was up to three times higher in pavements with a LCB than in those on ATB or aggregate base. Permeable aggregate bases performed very well and showed the least cracking. See Appendix A for further details.

Early age Cracking: Early age transverse cracking in the SPS-2 sections is illustrated in Figure 4. The sections used in this chart were in use for 2½ to 7 years and only 5 percent of the sections, i.e., 8 of the 155 sections, showed more than 50 percent cracking. These sections were all from Nevada that failed prematurely, possibly from construction and material problems (Stubstad, 2000).

Early age cracking was most prevalent on pavements with an LCB layer. PATB had the least cracking. This observation can again be attributed to the fact that the asphalt base is adequately stiff and yet “flexible” enough in its response.   A very stiff base material, such an LCB layer, causes more temperature-related deformation and can thus lead to premature transverse cracking. As expected, thicker slabs reduced transverse cracking considerably. It was also noted that sections in the wet-no freeze climatic zone showed the least early age transverse cracking and those in the dry-no freeze zone showed the highest.

Figure 4. Early age transverse cracking of JPCP in LTPP SPS-2 sections (Jiang et al., 2001).

Effect of Base Type on IRI

In general, it has been observed that pavements built smoother remain smooth longer. Pavements with a drainable base, and/or with an asphalt treated base, have the lowest overall International Roughness Indices (IRI) in the LTPP database. By and large, smoothness trends can be related to faulting trends. It was also found in the RPPR database that pavements with a stiff base have the higher IRI values (Smith et al., 1998).

Figure 5 shows the IRI observations in the early ages of JPCP sections in the LTPP SPS-2 sections (Jiang et al., 2001). Clearly, stiff bases and those with fines in the base material showed signs of increased roughness, perhaps due to a stronger and stiffer construction platform. The presence of a widened lane reduces joint faulting, even at early ages. An investigation into the effects of design features on initial IRI (Jiang et al., 2001), suggested that sections on permeable bases with edge drains had lower initial IRI values than those on treated bases. Furthermore, thinner slabs with lower 14-day concrete strength were built smoother than thicker slabs with high 14-day strength values.

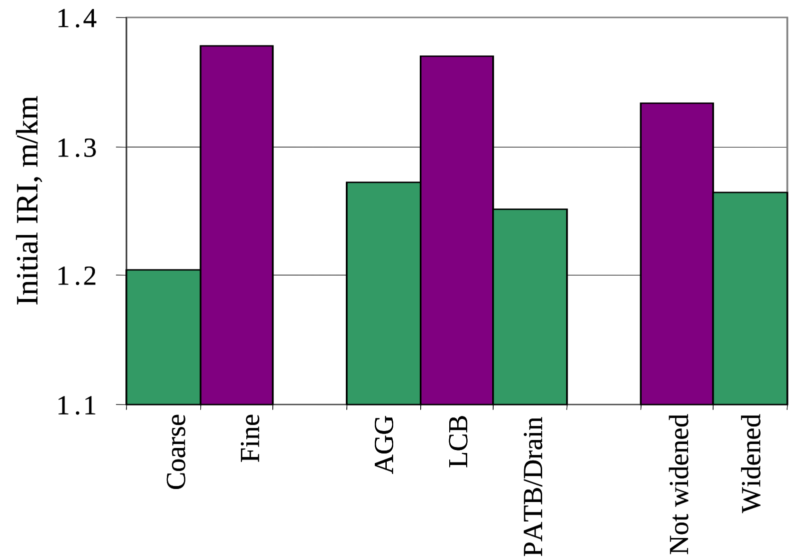

Figure 5. Early age IRI of JPCP in LTPP SPS-2 sections (Jiang et al., 2001).

3. STATISTICAL ANALYSIS OF RPPR AND LTPP DATABASES

The sections thus far in this report have discussed the influence of the base type (the independent variable) on each distress type (the dependent variables) in a general sense, i.e., without adequately accounting for the impact other design and site parameters may have on pavement performance. Therefore, to draw consistent and dependable conclusions, it would be ideal to compare sections that have all other variables constant, or in common, except for the base type (as was done in the RPPR study, relevant sections of which are included in Appendix A). However, in synthesizing information from large databases, as is being attempted in the present study (which uses both the RPPR and LTPP section data), it is essential to adopt statistical tools to assess the relationships between several independent variables and the dependent variable. In this case, the dependent variable is a performance criterion, such as joint faulting, cracking, or IRI, and the independent variables are the base type, traffic loads, climate, joint spacing, drainage, presence of a widened lane, and presence or absence of dowels. The statistical tool adopted in this analysis is the Generalized Linear Model (GLM) that has the capability to independently examine the influence of an independent variable on a dependent variable despite the presence of other predictor variables in the data sample (i.e., the GLM can isolate the effects of base type on pavement performance by normalizing the effect of drainage, joint spacing, dowels, and so on). The GLM predicts whether the effect of each independent variable is statistically significant on a dependent variable (distress type or pavement performance) using the analysis of variance (ANOVA) method.

The GLM is a generalization of the linear regression model and can accommodate:

- <u>Nonlinear</u> as well as <u>linear</u> effects of independent variables.
- <u>Categorical</u> predictor variables as well as <u>continuous</u> predictor variables.
- Dependent variable whose distribution follows several special members of the <u>exponential family of distributions</u> (e.g., gamma, Poisson, binomial, etc.), as well as <u>normally distributed</u> dependent variable.

The results of the GLM analysis performed for the effect of different independent parameters on a dependent variable are represented by the p-value for each parameter. The analysis was also extended to perform a "Duncan grouping" for the categorical variables used in the analysis. This method of grouping essentially conveys two important pieces of information. First, for each independent variable considered, those values (or categorical parameters) that are not statistically different in affecting the dependent variable are "grouped" together. This post-hoc comparison technique specifically takes into account the fact that many samples exist in the analysis. Next, the observed trends in the data are illustrated; in other words, for each independent variable used in the analysis, the GLM ranks the categorical parameters in decreasing values of the dependent variable. Interpretation of the statistical results is discussed further in this report, below.

Data Preparation

The data used in this statistical analysis consisted of data from the RPPR sections and sections from the LTPP SPS-2 and GPS-3 experiments. The data includes design parameters, climatic conditions, age, and cumulative traffic in ESALs for each distress observation. A comprehensive database was assembled to group data into categories most suitable for statistical analyses.

Special attention was accorded to assemble the data in a manner that would enhance the understanding of base type effects on pavement performance.

Since this large database was drawn from several sources, the terminology to describe certain variables was quite different. The researchers collated this information in a manner that lends consistency across the database and makes it amenable for targeted performance comparisons. This was done without altering the meaning and original intent of the LTPP and RPPR studies from which the data were extracted.

<u>Independent Variables Considered</u>: The parameters used in this analysis as independent variables for each dependent variable are summarized in Table 4. The table also indicates how each independent variable is treated in the analysis – as a continuous variable or as a categorical variable.

Based on the qualitative descriptions of the base types in the LTPP and RPPR studies, the different base types in the database were classified in the following six categories:

(1) DGAB for dense graded aggregate bases
(2) OGAB for permeable/open graded aggregate bases
(3) CTB for cement treated base with less than 8% stabilizing material
(4) LCB for lean concrete base with 8% or more stabilizing material
(5) ATB for dense asphalt treated base materials
(6) PATB for permeable/open graded asphalt base materials

Nearly 84 percent of the sections in the database had a joint spacing of 15 feet, while 12.5 percent of the sections had a joint spacing of 20 feet. The few remaining sections (about 3.5 percent) had joint spacings of 30 feet, 17 feet, 12 feet, and 8 feet. The joint spacings were therefore divided into two categories, LE15 for those less than or equal to 15 feet, and GT15 for those greater than 15 feet. The traffic on the pavement was considered as the total number of applied ESALs on the pavement until the time of distress observation. The four climate types considered in this analysis were based on the LTPP climate categories, wet-freeze, wet- no freeze, dry-freeze, and dry-no freeze. Drainage was also divided into four categories: daylighted, edge drains, none, and other. The data set included very few sections falling under the daylighted and other categories. The use of a widened lane in the design was divided into two categories – those with and those without a widened lane. Load transfer across joints was classified under two categories: doweled and none to represent sections with and without dowels, respectively. However, shoulder type and use of tie bars were not considered in the analysis. Other design features considered in the analysis were slab thickness and concrete modulus of rupture.

<u>Dependent Variables Considered</u>: As noted in Table 4, pavement performance indicators (dependent variables) used in this analysis were: edge faulting in inches, percent slabs with transverse cracking, and IRI in in/mile.

Table 4. Summary of variables used in statistical analysis.

Dependent variable	**Independent parameters**	**Continuous or Categorical**
IRI	Edge faulting	Continuous
	Percent cracking	Continuous
	Spalling	Continuous
	Percent corner breaks	Continuous
IRI	Climate	Categorical
	Traffic	Categorical
	Joint spacing	Categorical
	Thickness	Continuous
	Modulus of rupture	Continuous
	Widened lane	Categorical
	Base type	Categorical
	Doweled	Categorical
	Drainage	Categorical
Edge Faulting	Climate	Categorical
	Traffic	Categorical
	Joint spacing	Categorical
	Thickness	Continuous
	Modulus of rupture	Continuous
	Widened lane	Categorical
	Base type	Categorical
	Doweled	Categorical
	Drainage	Categorical
Percent Cracking	Climate	Categorical
	Traffic	Categorical
	Joint spacing	Categorical
	Thickness	Continuous
	Modulus of rupture	Continuous
	Widened lane	Categorical
	Base type	Categorical
	Doweled	Categorical
	Drainage	Categorical
Corner Breaks	Climate	Categorical
	Traffic	Categorical
	Joint spacing	Categorical
	Thickness	Continuous
	Modulus of rupture	Continuous
	Widened lane	Categorical
	Base type	Categorical
	Doweled	Categorical
	Drainage	Categorical

Results and Discussion

GLM and Duncan grouping analyses were performed at a confidence level of 90 percent for examining the effects of all independent variables on the variation of the dependent variable.

The selection of joint faulting and slab cracking as the key performance indicators is fairly obvious, since these are the variables with the most impact on the structural performance of jointed plain concrete pavements. The IRI term is a measure of functional pavement distress. However, the general notion is that IRI development over time is largely affect by the concurrent development of dominant pavement structural distresses, such as joint faulting and slab cracking, along with other construction-related and site factors. A GLM analysis was performed at a confidence level of 90 percent as a first step to confirm this hypothesis, the results of which are presented in Table 5. The level of significance is reported as the p-value. For a given independent variable, a p-value less than the confidence level indicates that the given variable statistically *does* have an effect on the dependent variable. Judging by the p-values reported in the table, it is clear that most of the distresses considered, with the exception of corner breaks, have a significant impact on IRI. Note that these p-values are less than 0.05, suggesting that they are significant even at a confidence level of 95 percent. This justifies the selection of slab cracking and corner breaks as the primary structural distress indicators. Therefore, understanding the role of base type in the development of these distresses is crucial to pavement design.

Table 5. Relative importance of various distresses on observed IRI.

Variable	p-value	Significance Rating
Edge Faulting	0.0001	***
Cracking	0.0093	***
Spalling	0.0001	***
Corner Breaks	0.1919	Poor

Next, GLM and Duncan grouping analyses were performed to examine the effects of the independent variables on three dependent variables, i.e. IRI, joint faulting, and cracking. Spalling was not included in the analyses.

Analysis for IRI: The GLM analysis results for the IRI, presented in Table 6, shows that the p-value is less than 0.1 for all variables, indicating that all the variables considered have a significant effect on IRI. Note that the p-values are less than 0.05 for most variables, suggesting that the effects of these parameters are significant even at a confidence level of 95 percent.

Table 7 summarizes the Duncan grouping for the categorical variables used in the analysis. In the grouping operation, the analysis ensures that the mean value of the dependent variable, IRI in this case, for each group is statistically different; in other words, the mean IRI for Group A is statistically different from that for Group B, both of which are different from the mean IRI for group C, and so on. For example, with regard to climate type affecting IRI, as shown in Table 7 the climate type wet-no freeze is classified as Group A, wet-freeze is classified as Group B, and dry-freeze and dry-no freeze are classified as Group C. This grouping pattern implies that the IRI values for those sections in wet-no freeze climates are significantly different from those in wet-freeze climates. Further, each of these two climate types in Groups A and B are statistically different from Group C, which consists of dry-freeze and dry-no freeze. Combining both dry-freeze, and dry-no freeze in the same group also implies that the IRI values are not significantly different for dry-freeze and dry-no freeze conditions. Further, the mean IRI values also indicate that wet-no freeze conditions result in the highest IRI values, while dry-freeze conditions result in the lowest IRI values.

Table 6. Relative importance of various site and design factors on observed IRI (at significance level of <0.1).

Variable	**p-value**	Significance Rating
Joint Spacing	0.0001	***
Widened Lane	0.0001	***
Base type	0.0001	***
Doweled	0.0001	***
Drainage	0.0001	***
Climate	0.001	**
Traffic (ESALs)	0.0013	**
Thickness	0.0568	*
Modulus of Rupture	0.0799	*

In a similar manner, the following conclusions are noted based on results shown in Table 7:

- JPCP sections with joint spacings of 15 feet or less are significantly smoother than pavements with longer joint spacings.
- JPCP sections with a widened lane are smoother than those without.
- The smoothest pavements are those with a PATB. Note that several factors contribute to smoothness, and a large percentage of cracked slabs and/or high joint faulting values will contribute to a relatively rough ride. JPCP sections with CTB are rougher than sections with any other base type, followed by those with open graded aggregate bases. The third highest IRI are seen in dense graded aggregate base sections. LCB and ATB have the next highest roughness, and their IRI values are typically in the same range.
- JPCP with doweled joints are significantly smoother than those without doweled joints.
- Daylighted JPCP sections have the highest IRI and the results indicate that sections with "other" drainage types have the lowest IRI. The multiple range Duncan grouping shows that, in terms of IRI performance, sections with daylighting fall in one group while the rest of the sections (those with no drains, edge drains, and "other" types of drains) fall in another distinct group. In other words, there is no difference in the IRI performance of pavements with no drains, edge drains, or "other" drainage types. However, note that there were only 8 sections with daylighting and 17 with "other" forms of drainage in the database. Therefore, the results for these two categories might not be very conclusive. What is surprising is the finding that the presence of edge drains had no impact on IRI performance when compared to sections with no edge drains at all. One significant factor

could be that the edge drains are not functioning as intended. The functionality of edge drains could not be verified in this study.

Table 7. Summary of Duncan grouping analysis for IRI.

Independent Variable Category	Category Level	Mean IRI, in/mi.	N	Duncan Grouping*
Climate	Wet-no freeze	125	167	A
	Wet-freeze	107	502	B
	Dry-freeze	89	259	C
	Dry-no freeze	89	163	C
Joint Spacing Type	> 15 ft	131	161	A
	≤ 15 ft	98	930	B
Presence of Widened Lane	No widening	108	760	A
	Widened lane	89	331	B
Base Type	CTB	134	164	A
	OGAB	116	24	B
	DGAB	104	441	C
	LCB	95	237	D
	ATB	94	52	D
	PATB	81	173	E
Presence of Dowels	No dowels	120	390	A
	Doweled	93	701	B
Drainage Type	Daylighted	125	8	A
	No drains	104	747	B
	Edge drains	101	319	B
	Other	94	17	B

* Levels within a given category, represented by different alphabets (e.g., Duncan grouping = A or B) are significantly different.

Analysis for Joint Faulting: The GLM analysis results for joint faulting, presented in Table 8, indicates that the p-value is less than 0.1 for all variables except traffic and modulus of rupture, indicating that all except these two variables have a significant effect on joint faulting. Note that the p-values are less than 0.05 for all controlling variables, suggesting that the effects of these parameters are significant even at a confidence level of 95 percent.

The fact that the modulus of rupture does not affect joint faulting is reasonable given that the modulus of rupture is more related to the cracking potential of the concrete and has a lesser bearing on the deflection characteristics of the pavement. However, joint faulting is known to increase with traffic. This apparent lack of effect of traffic on joint faulting is questionable, and can be caused by interaction between the parameters considered in the analysis or because the traffic parameter might need to be considered in a different form. Although interaction between the parameters was not an issue in this analysis, it was seen that the rate of application of traffic was significant in the faulting characteristics of the pavement. The traffic represented in ESALs was normalized over the age of the pavement, and the traffic parameter used in the analysis was changed to ESALs/year instead of just traffic in ESALs. This parameter not only represents the rate of traffic load application but also accounts for an increase in traffic for sections that have performance data over a long period of time. The results of this analysis are presented in Table 9. The significant effect of all the variables considered in the analysis on joint faulting is evident from this data. Note that it is also likely that only the highest load categories in the ESAL count are more significant on faulting performance. This was however, not investigated in this study.

Table 8. Relative importance of various site and design factors on observed joint faulting (at significance level of <0.1).

Variable	**p-value**	Significance Rating
Climate	0.0001	***
Joint Spacing	0.0001	***
Thickness	0.0002	***
Widened Lane	0.0001	***
Base Type	0.0001	***
Doweled	0.0001	***
Drainage	0.0001	***
Modulus of Rupture	0.4007	None
Traffic (ESALs)	0.9108	None

Table 9. Relative importance of various site and design factors on observed joint faulting using rate of application of traffic as an independent parameter.

Variable	**p-value**	Significance Rating
Climate	0.0001	***
Traffic (ESALs/year)	0.0001	***
Widened lane	0.0001	***
Base type	0.0001	***
Doweled	0.0001	***
Drainage	0.0001	***
Joint spacing	0.0140	**
Thickness	0.0719	**
Modulus of rupture	0.2200	None

Table 10 presents the results from a multiple range Duncan grouping analysis and gives a summary of the effect of all categorical parameters affecting joint faulting. It is worth pointing out that the Duncan grouping shows the same results for the two forms of traffic parameters – actual cumulative traffic (ESALs) and rate of traffic application (ESALs per year). Based on this information, the following conclusions can be made:

- JPCP sections in wet-no freeze climates have the largest joint faulting and this climate type falls in the first group, Group A. The second group, Group B, consists of wet-freeze and dry-no freeze climate types and this group has the second level of faulting. The third climate group, Group C, has only the dry-freeze climate with the lowest faulting values. This trend is as expected, because the group with the largest faulting characteristics has unfrozen moisture for extended periods during the year that contributes heavily to joint faulting. The second group consists of climate types that either have less moisture or have periods when the moisture is in a frozen condition, controlling faulting to some extent. The third group has the climate type that has little or frozen moisture and has the least potential for faulting if all other parameters are kept uniform across the climate types.

Table 10. Summary of Duncan grouping analysis for joint faulting.

Independent Variable Category	Category Level	Mean joint faulting, in.	N	Duncan Grouping*
Climate	Wet-no freeze	0.080	107	A
	Wet-freeze	0.038	202	B
	Dry-no freeze	0.037	118	B
	Dry-freeze	0.019	146	C
Joint Spacing Type	> 15 ft	0.077	86	A
	≤ 15 ft	0.034	487	B
Presence of Widened Lane?	No widening	0.053	410	A
	Widened lane	0.01	163	B
Base Type	CTB	0.092	87	A
	ATB	0.072	24	B
	OGAB	0.051	15	C
	DGAB	0.039	206	C D
	LCB	0.027	145	D
	PATB	0.009	96	E
Presence of Dowels	No dowels	0.087	199	A
	Doweled	0.016	374	B
Drainage Type	Daylighted	0.134	16	A
	No Drains	0.041	380	B
	Other	0.035	2	B
	Edge drains	0.032	175	B

* Levels within a given category, represented by different alphabets (e.g., Duncan grouping = A or B) are significantly different.

- JPCP sections with a joint spacing of 15 feet or less have significantly less joint faulting than sections with longer joint spacings.
- JPCP sections with a widened lane have significantly lower joint faulting than those without a widened lane.
- CTB and ATB are classified as Groups A and B, respectively, and have the highest faulting as a result of dense gradation in the base material and less stabilizing material in the CTB, thus allowing for the pumping of fines and poor drainage characteristics. The aggregate bases and LCB are grouped into the next two groups (note overlap of DGAB with OGAB and LCB). The last group consists of the permeable asphalt treated base, which shows the least faulting characteristics. PATB has the required permeability but is not as stiff, thus causing an increase in corner curl-up, making it a suitable base to control

faulting. However, the database did not have the information required to assess asphalt stripping in PATB layers.

- The presence of dowels has a significant advantage in controlling joint faulting.
- Daylighted JPCP sections have the highest joint faulting, and sections with edge drains have the lowest joint faulting. The multiple range Duncan grouping shows that, in terms of joint faulting performance, sections with daylighting fall in one group while the rest of the sections, i.e., those with no drains, edge drains, and “other” types of drains fall in another distinct group. In other words, there is no difference in the faulting performance of pavements with no drains, edge drains, or “other” drainage types. However, note that there were only 16 sections with daylighting and 2 with “other” forms of drainage in the database. Therefore, the results for these two categories might not be very conclusive. However, there is significantly lower mean faulting in sections with edge drains compared to those without any drainage. Again, the functionality of edge drains could not be verified in this study.

Analysis for Percent Slabs Cracked: The GLM analysis results for percent cracking, presented in Table 11, shows that the p-value is less than 0.1 for all variables except slab thickness and presence of dowels, indicating that all the variables considered, except slab thickness and the presence of dowels have a significant effect on joint faulting. Note that the p-values are less than 0.05 for almost all remaining variables, suggesting that the effects of these parameters are significant at a confidence level of 95 percent (except for lane width).

Table 11. Relative importance of various site and design factors on observed slab cracking (at significance level of 0.1).

Variable	**p-value**	Significance Rating
Modulus of rupture	0.0001	***
Climate	0.0027	**
Traffic (ESALs)	0.0016	**
Base type	0.003	**
Joint spacing	0.0241	*
Widened lane	0.0969	*
Drainage	0.048	*
Doweled	0.500	None
Thickness	0.4478	None

The presence of dowels is not particularly effective in reducing cracking in concrete pavements. Although dowels reduce differential slab deflections across transverse joints, transverse cracks are initiated and propagated by excessive edge stresses in the mid-length of the pavement. However, the fact that slab thickness does not affect transverse cracking is questionable. There could be at least two explanations for this:

- The JPCP sections used in this analysis were well-designed pavements and were built structurally adequate, or the slabs were thick enough to carry the projected traffic without cracking. Therefore a built-in bias exists in the database, such that the effect of thickness is not as apparent in the statistical analysis. The SPS-2 sections in the database for this analysis have several pairs of sections that have all other parameters in common except the slab thickness. The parameters in common include the base type, slab length, concrete modulus of rupture, traffic loads, and climate type. The analysis performed using only the SPS-2 section data showed evidence of a greater effect of slab thickness in the design, as shown in Table 12.

Table 12. Relative importance of various site and design factors on cracking.

Variable	p-value
Modulus of rupture	0.0001
Climate	0.0003
Widened lane	0.0018
Base type	0.0208
Traffic (ESALs)	0.0260
Thickness	0.1002
Joint spacing	N/A (same for all sections)
Doweled	N/A (same for all sections)
Drainage	N/A (same for all sections)

- There is an interaction between the modulus of rupture and thickness parameters in the database. This is also likely because the design thickness of the pavement is based on the modulus of rupture of the concrete. A GLM analysis accounting for the interaction between the modulus of rupture and slab thickness yielded a p-value of 0.0019 (<0.05) for this parameter, supporting evidence of the effect of both modulus of rupture and slab thickness, even at a confidence level of 95 percent.

Table 13 presents the results from multiple range Duncan grouping analysis and gives a summary of the effect of all categorical parameters affecting slab cracking. It is worth pointing out that the Duncan grouping shows the same results for the original analysis and the analysis using the interaction between modulus of rupture and thickness. The following conclusions can be made from this information:

- Hotter climates cause higher slab cracking than colder climates. It is also evident that the effect of temperature is more than that of moisture condition. The climate type grouped under Group A, wet-no freeze, results in the largest amount of slab cracking. The climate type wet-freeze, under Group C, has the lowest cracking. It appears that JPCP sections in the wet-no freeze condition develop significant tensile stresses in the bottom of the slab due to both positive temperature and moisture gradients, which are additive to the stresses resulting from traffic loads. However, those in wet-freeze climates develop stresses due to positive moisture gradients and negative temperature gradients that can effectively, at least in part, nullify the combined effect. It is to be noted here that temperature gradients reverse on a daily basis and moisture gradients are uniform over a season. It is also impractical to expect stresses from moisture and temperature nullifying the combined effects on a daily basis. However, the discussion presented is from analysis of data over several years and therefore only suggests the reasons for the observed trends.
- JPCP slabs with a length of 15 feet or less experience significantly less cracking than those with longer lengths.

Table 13. Summary of Duncan grouping analysis for slab cracking.

Independent Variable Category	Category Level	Slab cracking, percent	N	Duncan Grouping*
Climate	Wet-no freeze	14.2	117	A
	Dry-no freeze	8.2	122	B
	Dry-freeze	6.6	138	B
	Wet-freeze	3.0	238	C
Joint Spacing Type	> 15 ft	14.4	103	A
	≤ 15 ft	5.5	512	B
Presence of Widened Lane?	No widening	9.2	448	A
	Widened lane	1.0	167	B
Base Type	CTB	16.5	101	A
	LCB	8.3	151	B
	DGAB	5.5	220	B C
	ATB	4.6	27	B C
	OGAB	2.5	16	B C
	PATB	0.0	100	C
Presence of Dowels	No dowels	10.2	230	A
	Doweled	5.1	385	B
Drainage Type	Daylighted	10.7	14	A
	No drains	7.9	406	A
	Edge drains	5.0	192	A
	Other	2.0	3	A

* Levels within a given category, represented by different alphabets (e.g., Duncan grouping = A or B) are significantly different.

- The presence of a widened lane significantly reduces cracking in JPCP slabs.
- Stiffer bases, i.e. CTB and LCB, from Group A and B respectively, result in significantly more cracking than other base types considered in the analysis. The PATB base type is bracketed under Group C and has the lowest slab cracking. The other base types, DGAB, ATB and OGAB, have an overlap between Groups B and C. Based on this analysis, PATB bases perform the best while stiff bases exhibit the highest levels of cracking.
- Doweled pavements have less cracking than those without dowels.
- Daylighted JPCP sections have the highest slab cracking and sections with edge drains have the lowest. The multiple range Duncan grouping shows that, in terms of cracking performance, the four drainage types fall under the same category. However, it should be noted that there were only 14 sections with daylighting and 3 with “other” forms of drainage in the database. Therefore, the results for these two categories might not be conclusive. Again, the functionality of edge drains could not be verified in this study.

Base Type Effects on JPCP Performance for Each Climate, Slab Length, and Age Category

The data were further analyzed to investigate the effects of base type on JPCP performance with respect to climatic region, slab length, and pavement age. Results of the analysis based on climate type are presented in Table 14. The performance of JPCP sections based on slab length is presented in Table 15. Pavements with a joint spacing of 15 feet or less were grouped in one data set and those with a joint spacing of greater than 15 feet formed a second data set for this analysis.

Finally, the results of the analysis to examine the effects of pavement age are presented in Table 16. Pavements less than 10 years in age were considered “new” sections, and those greater than 10 years in age were considered “old” sections. To eliminate the effects of traffic while considering age, the data set was further divided based on amount of traffic. Sections with a cumulative traffic of 8 million ESALs or more were considered as heavily trafficked sections and those with less than 8 million ESALs were considered less trafficked sections. Therefore, while considering relatively new sections, those with excessive traffic were eliminated from the data set and the data set with old sections contained only sections that had also seen substantial traffic loads. Results for sections in the “old,” “new,” “old and heavily trafficked,” and “new and less trafficked” categories are presented in Table 16.

Table 14. Effect of base type on JPCP performance categorized by climate.

Type	Faulting				Transverse Cracking				IRI			
	Base Type	Mean	N	Duncan Group	Base Type	Mean	N	Duncan Group	Base Type	Mean	N	Duncan Group
Dry-freeze	CTB	0.103	6	A	CTB	10.0	9	A	CTB	128	27	A
	ATB	0.044	1	B	LCB	8.9	34	A	LCB	89	60	B
	DGAB	0.025	68	B C	DGAB	8.4	61	A	DGAB	86	112	B
	LCB	0.008	39	C	OGAB	4.3	7	A	PATB	83	40	B
	PATB	0.005	28	C	ATB	0	2	A	ATB	72	10	C
	OGAB	0.003	7	C	PATB	0	28	A	OGAB	66	12	C
Dry-no freeze	CTB	0.096	33	A	CTB	18.6	33	A	CTB	117	36	A
	LCB	0.021	37	B	LCB	9.5	41	B	DGAB	89	48	B
	DGAB	0.008	31	C	DGAB	0.1	31	C	LCB	76	50	C
	PATB	0.008	17	C	PATB	0	17	C	PATB	75	29	C
Wet-freeze	ATB	0.159	9	A	ATB	4.5	11	A	CTB	150	31	A
	CTB	0.101	10	B	DGAB	4.3	108	A	ATB	118	19	B
	DGAB	0.043	89	C	CTB	4.0	12	A	DGAB	113	245	B
	OGAB	0.030	6	C D	LCB	2.9	48	A	LCB	103	98	B
	LCB	0.019	40	C D	OGAB	0.8	7	A	OGAB	102	7	B
	PATB	0.010	49	D	PATB	0	53	A	PATB	82	103	C
Wet-no freeze	OGAB	0.212	3	A	CTB	19.4	47	A	OGAB	227	6	A
	DGAB	0.114	20	B	LCB	15.1	28	A	CTB	138	70	B
	CTB	0.084	38	B C	DGAB	10.6	23	A	DGAB	119	39	B C
	LCB	0.073	29	B C	ATB	5.1	15	A	LCB	112	29	B C D
	PATB	0.050	1	C D	OGAB	1.3	3	A	PATB	93	1	C D
	ATB	0.018	15	D	PATB	0	1	A	ATB	83	23	D

Table 15. Effect of base type on JPCP performance categorized by joint spacings.

Type	Faulting				Transverse Cracking				IRI			
	Base Type	Mean	N	Duncan Group	Base Type	Mean	N	Duncan Group	Base Type	Mean	N	Duncan Group
SHORT (Slab length of 15 feet or less)	CTB	0.094	60	A	CTB	14.4	67	A	CTB	131	104	A
	ATB	0.074	23	B	LCB	8.1	125	B	DGAB	101	393	B
	DGAB	0.034	177	C	ATB	4.9	25	B C	ATB	97	42	B
	LCB	0.021	122	D C	DGAB	3.8	186	B C	LCB	92	204	B
	OGAB	0.015	13	D	OGAB	2.6	14	B C	PATB	81	173	C
	PATB	0.009	95	D	PATB	0.0	99	C	OGAB	80	19	C
LONG (Slab length more than 15 feet)	OGAB	0.212	3	A	CTB	20.7	34	A	OGAB	227	6	A
	CTB	0.087	27	B	DGAB	14.2	37	A	CTB	139	60	B
	DGAB	0.070	31	B	LCB	9.4	26	A	DGAB	131	51	C B
	LCB	0.062	23	C B	ATB	1.3	3	A	LCB	114	33	C
	ATB	0.014	2	C	OGAB	1.3	3	A	ATB	78	10	D

Table 16. Effect of base type on JPCP performance categorized by age.

Type	Faulting				Transverse Cracking				IRI			
	Base Type	Mean	N	Duncan Group	Base Type	Mean	N	Duncan Group	Base Type	Mean	N	Duncan Group
New Sections (age less than 10 years)	CTB	0.051	10	A	CTB	15.7	15	A	CTB	104	23	A
	DGAB	0.016	129	B	LCB	7.1	103	B	DGAB	95	275	A
	OGAB	0.015	13	B	DGAB	4.3	139	B	LCB	94	189	A
	ATB	0.015	7	B	OGAB	2.6	14	B	OGAB	80	19	B
	LCB	0.014	102	B	ATB	0.0	8	B	PATB	80	167	B
	PATB	0.007	88	B	PATB	0.0	92	B	ATB	79	15	B
Old Sections (age more than 10 years)	OGAB	0.212	3	A	CTB	16.6	86	A	OGAB	227	6	A
	CTB	0.097	77	B	LCB	11.0	48	B A	CTB	139	141	B
	ATB	0.091	18	B	DGAB	7.6	84	B A	DGAB	119	169	C B
	DGAB	0.077	79	B	ATB	6.4	20	B A	PATB	113	6	C
	LCB	0.060	43	C B	OGAB	1.3	3	B A	ATB	99	37	C
	PATB	0.025	7	C	PATB	0.0	7	B	LCB	98	48	C
New and Less Trafficked Sections	CTB	0.047	7	A	CTB	16.9	12	A	CTB	104	19	A
	OGAB	0.020	11	B	LCB	5.4	77	B	LCB	94	129	B
	DGAB	0.018	96	B	DGAB	4.6	108	B	DGAB	94	205	B
	LCB	0.017	75	B	OGAB	1.8	12	B	PATB	83	111	C
	ATB	0.015	7	B	ATB	0.0	8	B	OGAB	81	15	C
	PATB	0.009	60	B	PATB	0.0	64	B	ATB	79	15	C
Old and trafficked Sections	CTB	0.113	34	A	ATB	25.8	3	A	PATB	170	1	A
	DGAB	0.096	14	B A	CTB	24.8	40	A	CTB	158	55	A
	LCB	0.069	26	B C	LCB	17.2	29	A	DGAB	132	22	A
	PATB	0.050	1	D C	DGAB	12.0	15	A	LCB	79	25	B
	ATB	0.013	3	D	PATB	0.0	1	A	ATB	77	11	B

Base type effects on JPCP performance for each climate category: The results shown in Table 14 summarize the mean faulting, transverse cracking, and IRI for each base type and for all climate categories. The base types are ranked in order of their performance. Also shown is N, the number of data points available in each base type / climate type combination. The number of data points is critical in assessing the reliability of the grouping or mean value. In general, the following conclusions can be drawn from Table 14 regarding the effect of base type on pavement performance as a function of climatic zone:

- It appears that the faulting performance within each climatic zone is sensitive to the base type. Discounting instances where the number of observations (N) was less than 10, it appears that in a majority of the cases, regardless of climate type, the faulting performance of pavement sections with DGAB was statistically different (worse) than those with either PATB or ATB. The only exception to this general trend is the faulting performance in a dry-no freeze climatic zone. For this climatic condition, there is no statistical difference in the performance of sections with DGAB and PATB. However, the faulting performance of pavement sections with CTB and LCB was worse than those with DGAB.
- There does not appear to be a significant impact of base type on transverse cracking performance in any of the four climatic zones, with the exception of the dry-no freeze climate. For this climatic type, sections with CTB had the highest amount of cracking and those with LCB had the next highest. This is possibly due to collective effects of both dry and high temperature conditions. The performance of sections with CTB and LCB was also statistically different. The best performing sections in terms of transverse of cracking were the DGAB and PATB sections, which showed statistically indistinguishable results. In the wet-freeze climatic region, it was noted that a higher proportion of slabs on ATB and DGAB base types had a joint spacing of greater than 15 feet, which would explain the higher transverse cracking in those sections.
- Base type affects IRI performance in the same manner as it affects faulting performance within each climate type. This is not surprising considering that pavement smoothness as reflected by the IRI value is heavily dependent on joint faulting.

Base type effects on JPCP performance for each joint spacing category: The following conclusions can be drawn from Table 15 regarding the effect of base type on pavement performance as a function of joint spacing. It must be noted that in drawing the conclusions stated below, base type categories with less than 10 observation points (N) were not considered. The results are presented in two categories – slabs with joints at 15 ft intervals or less and slabs with joint spacing greater than 15 ft.

- Generally speaking, it is apparent from that table that mean levels of all three distresses under consideration are less when slab lengths are 15 feet or less. This is particularly apparent when considering mean joint faulting and IRI data for a given base type across the two joint spacing categories.
- It appears that base type has a significant effect on joint faulting performance. However, the relative effects of base type on joint faulting are similar in both joint spacing categories. In other words, faulting performance is affected by base type

in more or less the same way regardless of the joint spacing in question. For example, when joint spacing is 15 ft or less, slabs with CTB show the highest mean faulting along the project followed by ATB, DGAB, and LCB. Likewise, for sections with joint spacing greater than 15 ft (discounting the results from the OGAB and ATB sections [N < 10]), sections with CTB show the highest faulting followed by DGAB and LCB. Both higher curling strains (in sections with CTB and LCB) and high percentages of erodible fines (in sections with DGAB) could be a factor contributing to sections with these base types showing higher levels of faulting. As expected, due to the ability of OGAB and PATB to remove moisture from within the joint – a critical factor contributing to faulting, sections with these base types exhibit the least amount of faulting.

- It appears that the base type effect on cracking performance is much more significant in slabs with short joint spacing than those with longer spacings. This is perhaps because, in the latter case, the effect long slab lengths have on cracking (due to higher curling and load-related strains) are more significant and confound any differences in slab cracking due to base type alone. This is true at least when considering the performance of sections with CTB, DGAB, and LCB (results from ATB and OGAB are disregarded since N < 10). Therefore, as far as cracking performance is concerned, the differences between CTB, DGAB, and LCB are statistically insignificant when slab lengths are greater than 15 feet. On the other hand, when slab lengths are 15 ft or less, sections with CTB and LCB have the highest slab cracking due to the higher curling and warping stresses in these slabs, followed by ATB, DGAB, OGAB and PATB, respectively. In fact, the latter four base types can be considered as being part of the Duncan group, i.e., slab cracking across these categories is not statistically different.
- The trends in IRI performance vis-à-vis base type and joint spacing are very similar to that of faulting performance, once again because faulting and IRI correlate very strongly. For sections with joint spacing of 15 ft or less, the IRI values are arranged in the following ordered groups, from worse to best performance: Group A – CTB, Group B – DGAB, ATB, LCB, and Group C – PATB, OGAB. For sections with joint spacing of more than 15 ft (after discounting data from the OGAB sections with N < 6), the Duncan groups from worse to best performance are: Group B – CTB and DGAB, Group C – LCB, and Group C – ATB. Note that the total number of observations for the ATB sections were only 10 and therefore the results should be treated with due care.

<u>Base type effects on JPCP performance for each age category</u>: In Table 16, the effect of base type on pavement performance as a function of age alone, as well as age and traffic, is presented. The discussion below focuses on the performance comparisons as a function of combined age and traffic since this is generally considered more meaningful than basing the comparisons on age alone. To further enunciate the difference between short- and long-term performance, two extreme cases within the combined category of age and traffic were chosen and are highlighted in the table – performance of relatively newer sections with low traffic levels versus older sections with high traffic levels. As has been done previously, in making performance comparisons, base type categories with

less than 10 observation points (N) were not considered. Some of the key findings of this analysis are:

- Generally speaking, newer and less trafficked sections with a given base type seem to exhibit less faulting and cracking, and lower IRI values, when compared to similar sections which are older and have been subjected to higher traffic levels.
- An examination of the faulting data shows that for newer, less trafficked sections, base type does not seems to have an impact on mean joint faulting (CTB and ATB were not considered in the comparison), meaning that the magnitudes of observed mean faulting for OGAB, DGAB, LCB, and PATB were not statistically different. This is perhaps due to the fact that very little faulting was observed in the first place in all these sections. However, for older, heavier trafficked sections, CTB seems to cause a statistically higher amount of faulting than LCB with DGAB. There were an inadequate number of PATB sections to draw any definite conclusions regarding their long-term behavior.
- For newer and less trafficked sections, CTB sections indicate a statistically high degree of cracking, when compared to the rest of the sections which all fall under the same Duncan grouping. However, the older and more heavily trafficked sections do not show a statistically significant difference in the cracking performance as a function of base type. Other factors, such as base type and pavement thickness, could be confounding the results.
- In terms of the IRI performance, in the newer and less trafficked category, PATB CTB, LCB, and DGAB sections have higher IRI values, followed by PATB, OGAB, and ATB with lower values. One reason for this difference in early IRI values could be that, all other factors such as construction techniques, incentive and disincentive schemes, etc., being equal, initial smoothness of these sections could be a function of base type. Obviously, this needs to be investigated further to confirm the results. Among the older and more heavily trafficked sections, CTB and DGAB are among the roughest, followed by LCB and ATB (although only limited observations [N=11] are noted for this base type).

4. BASE TYPE CONSIDERATIONS IN DESIGN

1998 AASHTO Design

The 1998 AASHTO design procedure underwent an improvement over the previous versions, and specifically incorporated an improved characterization of subgrade support. This version also considers the base layer as a structural layer in the pavement and provides improved guidance on base type selection. Based on the 1998 AASHTO design for concrete pavements, the effects of base type in the traffic carrying capacity of JPCP pavements is illustrated in Figure 6 and Figure 7.

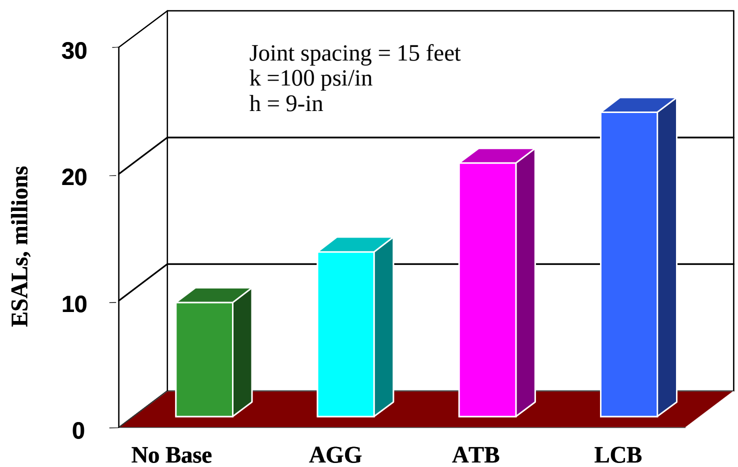

Figure 6. Effect of base type on design traffic based on 1998 AASHTO design.

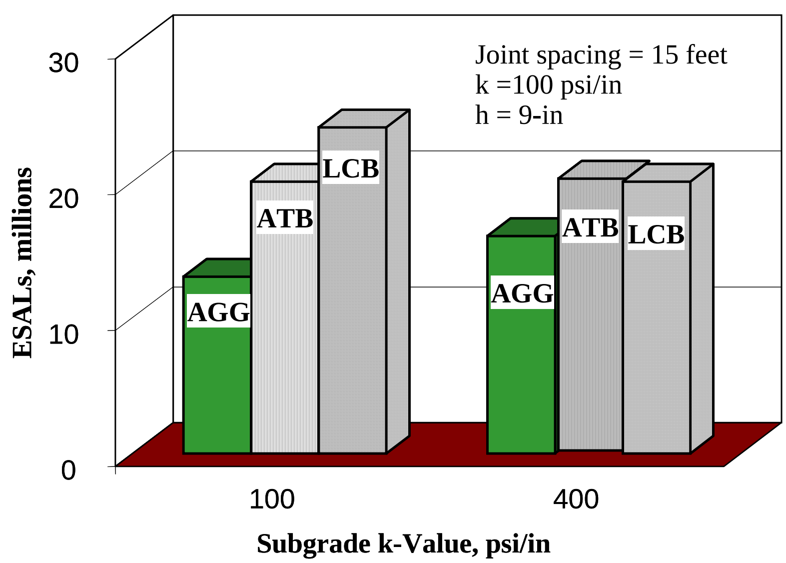

Figure 7. Effect of base type and k-value on design traffic based on 1998 AASHTO design.

The confounding effects of the strength of the subgrade can be seen in Figure 7. Aggregate bases lend a higher traffic-carrying capacity to pavements on high-strength subgrades than on low-strength subgrades. Also, treated bases are more effective on a low-strength subgrade than on a high-strength subgrade.

2002 Design Guide

The 2002 Design Guide, developed as part of the National Council of Highway Research Program (NCHRP) Project 1-37A, includes sophisticated mechanistic-empirical models to predict JPCP performance for a given climatic location. The 2002 Design Guide models account for changing climate, material, and traffic conditions, and predict the performance of the pavement over the design life. Critical responses due to traffic and environmental conditions are determined using mechanistic principles, and performance models calibrated using field data predict distress accumulation over the design life. For JPCP section, the critical distress types considered in performance prediction are joint faulting, transverse cracking, and IRI.

The inputs provided to the 2002 Design Guide procedure are key to the performance predicted by the models. The base type effects are predicted, not purely on the type of (name of) base material used in the pavement design, but on the basis of the layer properties assigned to the base. The base modulus, erodibility, thickness, subgrade modulus and gradation, climatic conditions, built-in temperature and moisture gradients in slab, joint spacing, slab thickness, and traffic levels (axle load distributions) are some of the factors that affect JPCP performance. In using the 2002 Design Guide models, it is to be noted that the analysis tools can model all factors that can be considered mechanistic-empirically. Several unpredictable aspects of field pavements and elements that cannot be quantified, such as failure of drainage, variability in friction, poor or variability in construction, etc., cannot be modeled. The 2002 Design Guide is close to completion and will be officially submitted to the NCHRP shortly.

SUMMARY

The base layer underneath the PCC slab does not necessarily contribute to the structural capacity of the JPCP section; it provides a uniform and stable construction platform, and improves the subdrainage. However, it has a significant effect on the performance of the JPCP because the base type has a direct impact on the extent of erosion in the subbase, drainage in the pavement, slab lift-off (curling and warping) in the PCC slab. These factors make the base type a critical issue in the resulting faulting, cracking and smoothness. This report summarizes findings on base type effects from previous studies and presents a statistical analysis of field data from LTPP and RPPR tests to illustrate the effects of base type on JPCP sections in general. Furthermore, the analysis is also extended to base type effects on JPCP for specific climate type, joint spacing and pavement age.

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APPENDIX – A
Effect of Base Type on Performance of JPCP

(Section from publication FHWA-RD-95-110 "Performance of Concrete Pavements, Vol. II: Evaluation of In-service Pavements, Chapter 3- Effect of Design Features on Pavement Performance, pp. 108-136)

APPENDIX – B
Effect of Base Type on Performance of JPCP

(Section from FHWA-RD-95-110 "Performance of Concrete Pavements, Vol. II: Evaluation of In-service Pavements, Chapter 3- Effect of Design Features on Pavement Performance, pp. 108-136)

Key JPCP performance data in the RPPR field sections are summarized in this appendix. The data is presented as the average level of distress for different slab length categories and for each base type. The average traffic associated with each distress type is also tabulated in this summary. It is important to note that the number of sections present in the database for each combination of base type, length, and climate is not the same. Therefore, some trends observed purely from these data could be questionable.

Average joint faulting in the RPPR sections for each climate type is summarized in Tables B1, B2, and B3 for joint spacings of 15, 20, and 30 feet, respectively. Tables B4, B5, and B6 show summaries of average transverse cracking in the RPPR sections by climate type for 15-, 20-, and 30-foot joint spacings, respectively. Tables B7, B8, and B9 show summaries of average IRI in the RPPR sections by climate type for 15-, 20-, and 30-foot joint spacings, respectively. The fact that the sample size is not evenly distributed across all combinations of slab length-traffic-climate type poses some and some observed trends could be misleading in these data.

Table B1. Average faulting and traffic in RPPR sections with 15-ft joint spacing.

Base type	DN		DF		WN		WF	
	Faulting inch	Traffic mil Esal	Faulting inch	Traffic mil Esal	Faulting inch	Traffic mil Esal	Faulting inch	Traffic mil Esal
CTB	0.11	10.2	-	-	0.09	6.2	0.04	49.2
AGG	-	-	0.05	4.3	-	-	0.05	1.4
AC/PCTB	0.13	5.1	-	-	-	-	0.02	1.3
ATB	0.05	7.2	-	-	-	-	0.20	1.1
LCB	0.02	7.6	-	-	0.05	4.5	0.09	1.5
None	0.02	5.2	-	-	-	-	0.08	1.5
PAGG	-	-	-	-	-	-	0.03	3.0
PATB	-	-	-	-	0.05	1.0	0.03	1.3
Sand	-	-	-	-	0.05	9.5	-	-

Table B2. Average faulting and traffic in RPPR sections with 20-ft joint spacing.

Base type	DN		DF		WN		WF	
	Faulting Inch	Traffic mil Esal	Faulting inch	Traffic mil Esal	Faulting inch	Traffic mil Esal	Faulting inch	Traffic mil Esal
CTB	-	-	-	-	0.04	19.1	-	-
AGG	-	-	-	-	0.06	6.9	0.06	3.7
AC	-	-	-	-	0.03	19.1	-	-
ATB	-	-	-	-	0.01	19.1	0.02	4.3
LCB	-	-	-	-	0.04	8.5	-	-
None	-	-	-	-	-	-	0.14	5.5
PAGG	-	-	-	-	-	-	-	-
PATB	-	-	-	-	-	-	-	-
Sand	-	-	-	-	-	-	-	-
Soil cement								

Table B3. Average faulting and traffic in RPPR sections with 30-ft joint spacing.

Base type	DN		DF		WN		WF	
	Faulting Inch	Traffic mil Esal	Faulting inch	Traffic mil Esal	Faulting inch	Traffic mil Esal	Faulting inch	Traffic mil Esal
CTB	-	-	-	-	0.16	12.5	-	-
AGG	-	-	-	-	0.16	12.5	-	-
AC	-	-	-	-	-	-	-	-
ATB	-	-	-	-	0.04	12.5	-	-
LCB	-	-	-	-	-	-	-	-
None	-	-	-	-	-	-	-	-
PAGG	-	-	-	-	-	-	-	-
PATB	-	-	-	-	-	-	-	-
Sand	-	-	-	-	-	-	-	-
Soil cement	-	-	-	-	0.15	12.5	-	-

Table B4. Average cracking and traffic in RPPR sections with 15-ft joint spacing.

Base type	**DN**		**DF**		**WN**		**WF**	
	Cracking percent	Traffic mil Esal	Cracking percent	Traffic mil Esal	Cracking percent	Traffic mil Esal	Cracking percent	Traffic mil Esal
CTB	25.35	10.2	-	-	15.73	6.2	2.52	49.2
AGG	-	-	0.14	4.3	-	-	0.30	1.4
AC/PCTB	1.43	5.1	-	-	-	-	0.00	1.3
ATB	0.00	7.2	-	-	-	-	6.62	1.1
LCB	12.35	7.6	-	-	0.19	4.5	11.26	1.5
None	2.58	5.2	-	-	-	-	0.00	1.5
PAGG	-	-	-	-	-	-	0.88	3.0
PATB	-	-	-	-	0.00	1.0	0.00	1.3
Sand	-	-	-	-	0.00	9.5	-	-

Table B5. Average cracking and traffic in RPPR sections with 20-ft joint spacing.

Base type	**DN**		**DF**		**WN**		**WF**	
	Cracking percent	Traffic mil Esal	Cracking percent	Traffic mil Esal	Cracking percent	Traffic mil Esal	Cracking percent	Traffic mil Esal
CTB	-	-	-	-	0.00	19.1	-	-
AGG	-	-	-	-	2.94	6.9	18.99	3.7
AC	-	-	-	-	0.00	19.1	-	-
ATB	-	-	-	-	0.00	19.1	4.39	4.3
LCB	-	-	-	-	1.60	8.5	-	-
None	-	-	-	-	-	-	0.80	5.5
PAGG	-	-	-	-	-	-	-	-
PATB	-	-	-	-	-	-	-	-
Sand	-	-	-	-	-	-	-	-
Soil cement	-	-	-	-	2.00	4.5	13.50	5.5

Table B6. Average cracking and traffic in RPPR sections with 30-ft joint spacing.

Base type	**DN**		**DF**		**WN**		**WF**	
	Cracking percent	Traffic mil Esal	Cracking percent	Traffic mil Esal	Cracking percent	Traffic mil Esal	Cracking percent	Traffic mil Esal
CTB	-	-	-	-	4.29	12.5	-	-
AGG	-	-	-	-	25.71	12.5	-	-
AC	-	-	-	-	-	-	-	-
ATB	-	-	-	-	0.00	12.5	-	-
LCB	-	-	-	-	-	-	-	-
None	-	-	-	-	-	-	-	-
PAGG	-	-	-	-	-	-	-	-
PATB	-	-	-	-	-	-	-	-
Sand	-	-	-	-	-	-	-	-
Soil cement	-	-	-	-	5.11	12.5	-	-

Table B7. Average IRI and traffic in RPPR sections with 15-ft joint spacing.

Base type	**DN**		**DF**		**WN**		**WF**	
	IRI	Traffic mil Esal	IRI	Traffic mil Esal	IRI	Traffic mil Esal	IRI	Traffic mil Esal
CTB	152	10.2	-	-	134	6.2	163	49.2
AGG	-	-	161	4.3	-	-	131	1.4
AC/PCTB	137	5.1	-	-	-	-	139	1.3
ATB	148	7.2	-	-	-	-	202	1.1
LCB	108	7.6	-	-	113	4.5	156	1.5
None	127	5.2	-	-	-	-	146	1.5
PAGG	-	-	-	-	-	-	102	3.0
PATB	-	-	-	-	93	1.0	108	1.3
Sand	-	-	-	-	93	9.5	-	-

Table B8. Average IRI and traffic in RPPR sections with 20-ft joint spacing.

Base type	DN		DF		WN		WF	
	IRI	Traffic mil Esal	IRI	Traffic mil Esal	IRI	Traffic mil Esal	IRI	Traffic mil Esal
CTB	-	-	-	-	52	19.1	-	-
AGG	-	-	-	-	186	6.9	139	3.7
AC	-	-	-	-	59	19.1	-	-
ATB	-	-	-	-	49	19.1	110	4.3
LCB	-	-	-	-	122	8.5	-	-
None	-	-	-	-	-	-	116	5.5
PAGG	-	-	-	-	-	-	-	-
PATB	-	-	-	-	-	-	-	-
Sand	-	-	-	-	-	-	-	-
Soil cement	-	-	-	-	147	4.5	-	-

Table B9. Average IRI and traffic in RPPR sections with 30-ft joint spacing.

Base type	DN		DF		WN		WF	
	IRI	Traffic mil Esal	IRI	Traffic mil Esal	IRI	Traffic mil Esal	IRI	Traffic mil Esal
CTB	-	-	-	-	143	12.5	-	-
AGG	-	-	-	-	117	12.5	-	-
AC	-	-	-	-	-	-	-	-
ATB	-	-	-	-	106	12.5	-	-
LCB	-	-	-	-	-	-	-	-
None	-	-	-	-	-	-	-	-
PAGG	-	-	-	-	-	-	-	-
PATB	-	-	-	-	-	-	-	-
Sand	-	-	-	-	-	-	-	-
Soil cement	-	-	-	-	115	12.5	-	-